

Immersive Environments for Mission Operations: Beyond Mars Pathfinder

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ABSTRACT

Immersive environments are just beginning to be used to support mission operations at the Jet Propulsion Laboratory. This technology contributed to the Mars Pathfinder Mission in planning sorties for the Sojourner rover. Utilizing stereo imagery from the Imager for Mars Pathfinder (IMP) camera enabled the operator to visualize the terrain from the lander's point of view in 3D to assist in plotting waypoints. In addition, the stereo imagery was used to create 3D terrain models which could be viewed from any angle to provide an additional visualization tool. These technologies contributed heavily to both the mission success and the phenomenal level of public outreach achieved by Mars Pathfinder. This paper will review the utilization of immersive environment technology in support of Mars Pathfinder and discuss development beyond Pathfinder and future directions in detail.

Future developments in immersive environments for mission planning include several tools which make up a system for performing and rehearsing missions. This system includes tools for planning long range sorties for highly autonomous rovers, tools for building the three-dimensional (3D) models of the terrain being explored, and advanced tools for visualizing telemetry from remote spacecraft and landers. In addition, Web-based tools for scientific collaboration in planning missions, as well as performing public outreach and education, are under development. These tools comprise a system for immersing the operator in the environment of another planet, body, or space to make the mission planning function more intuitive and effective.

Keywords: Immersive environments, Pathfinder, Sojourner, terrain modelling, visualization, Mars, MVACS.

1.0 Introduction

The application of immersive environments to mission operations within the Visualization and Earth Sciences Applications (VESA) Group at the Jet Propulsion Lab began with the Sense of Active Presence (SOAP) task. The group has been involved in scientific data visualization for various missions and has produced a variety of well-known animations including "L.A.: The Movie" with flights over the Los Angeles basin and San Andreas fault and "Mars: The Movie" with flights over the Candor Chasma area. The SOAP task was the first to apply the terrain modelling and animation techniques developed within the group in a rapid turnaround mode to support mission operations. During the Mars Pathfinder mission, tools developed within the SOAP task produced 3D models of the terrain around the lander for use in generating and reviewing operations sequences for the Sojourner rover.

Current tasks within the group are extending the success of the SOAP task in developing a more coherent and overall system for immersive operations. The SOAP task is extending the Rover Control Workstation (RCW) used during Pathfinder to incorporate 3D visualization in a more integrated manner. The Robotic Arm Mission Planning System (RAMPS) task is integrating various subsystems for creating 3D terrain models from orbiter, descent, lander, and rover imagery. These terrain models will be used to support the Mars Volatiles and Climate Surveyor (MVACS) experiment on board Mars '98. The Advanced Telemetry Visualization (ATV) task uses 3D visualization for reviewing mission operations through playback of telemetry returned from the craft and will also be used to support MVACS. The Web Interface for TeleScience (WITS) task is developing a Web-based tool for scientific collaboration in setting science mission goals and objectives and creating science operations sequences in support of MVACS.

2.0 Sense of Active Presence

The goal of this task is to develop the next generation of rover mission planning and data analysis tools. These tools will be based on giving the operator a "sense of presence" in the rover's environment. This system will give the user the sense of being immersed in the environment the rover is investigating with the freedom to examine scientific data without being bound to the point-of-view of the rover. Initially it was felt that utilization of head-mounted displays and head trackers would be ideal. Studies done during the first year of the task indicate that this type of immersion is good for certain types of tasks but that other systems and modalities are more effective for other types of tasks. An additional mode arising from this study is a plan view on a "Virtual Workbench" type of display providing a high-resolution, stereo display of a terrain region in a map-like layout intuitive to route planners. A third mode of free-flight through the region using stereo displays is also effective for some types of tasks.

Programming the rover to perform a sortie can be a laborious process as every possible obstacle must be analyzed and the safest route selected. Control-feedback loop turnaround times in minutes or hours preclude direct control of a rover in a man-in-the-loop configuration. Future generations of rovers will roam far from their landing sites, sometimes out of line-of-sight communications range. To support this capability, rovers will include onboard intelligence to perform a higher level of sortie planning, navigation, and obstacle avoidance than has been possible to date. This new paradigm of rover functionality will call for a new type of operator control, with much more interaction with the environment and less low-level control of rover operations. This new modality will utilize data visualization technology to provide a multi-dimensional "sense of presence" for operation and data analysis of teleoperated and semiautonomous vehicles. This will give the operator, or mission planner, the freedom to roam the vehicle's environment, thus providing a more intuitive and richer human/computer interface. The operator will be able to explore potential sites through the interface prior to committing the rover. Routes and destinations can be preexamined and designated through the interface. This adaptation of commercial technologies to the flight system environment will provide a more sophisticated and intuitive interface for human interaction with exploration vehicles and provide a better understanding of in-situ operations leading to better decision making. An additional benefit is the use of the sense of presence interface for analysis and interaction with the science data, both by researchers and by the educational community and the public.

This task involves the development of an immersive environment for scientific data analysis and autonomous vehicle control, providing a sense of presence within the vehicle's environment. Figure 1 shows how the immersive operator station fits within the control loop of a typical autonomous exploration vehicle. Both the vehicle and the operator station begin with an initial database describing the terrain to be explored. This database will typically be created with descent imagery and lander panoramic data merged with previously available data from orbiters or Earth-based sensors. The operator will be immersed in a visual database, which may contain infrared data or information from other sensors but which will be presented to the operator visually. The operator explores the database, selecting interesting areas to explore and designating desired routes. The rover will receive this planning information, comparing potential routes with

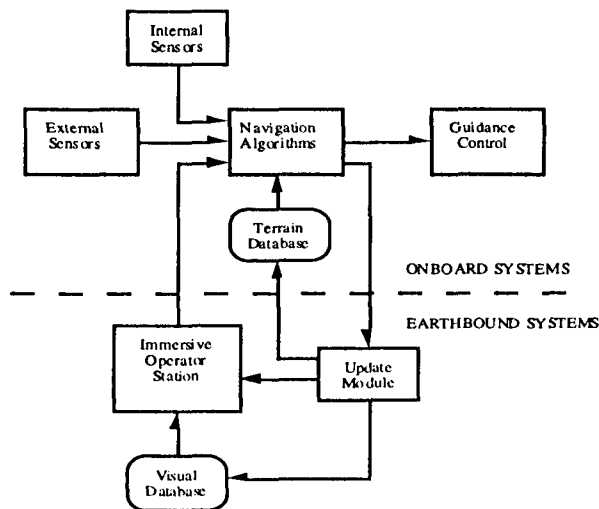


Figure 1: Rover Navigation System Block Diagram



Figure 2: Computer Rendered MPF Landing Site

its terrain database to identify hazards, and select a route. The vehicle will traverse the route, using alternative routes as appropriate to avoid previously unknown hazards, and transmit imagery and other data back to the ground station within operational constraints. As new data is received, the visual and material databases are updated, essentially filling in the coarse picture with high-resolution information. Any part of the visual database may be explored at any time and multiple individuals may access the database at the same time. This allows researchers and educators access to data in parallel with the operators.

The SOAP task has realized several achievements to date, including experimentation with head-mount displays (HMD), evaluation of several rival immersive technologies, and development of a prototype terrain modelling and visualization system used during the Pathfinder mission. The prototype visualization system was integrated with the existing rover control workstation to augment the stereo image module with a 3D model visualization capability. Examples of the 3D visualizations from this tool were featured on media coverage of the Pathfinder mission. Figure 2 shows a view of the 3D terrain area around the Pathfinder lander. The image shows a view from above the lander looking toward Yogi which is just right of center.

Several tools were developed to support this capability. These include software to filter correlated stereo images from the IMP camera, a tool to convert the filtered range images to 3D models, and a tool to combine the models into a single, viewable region. Some of these models were released as VRML worlds to the public over the Internet. In addition, another tool was developed which can convert the 3D model into a special model format which can be used to generate a physical model using computer aided manufacturing or rapid prototyping techniques.

3.0 Immersive Techniques Evaluated

The Sense Of Active Presence (SOAP) task seeks to develop an immersive environment for controlling exploratory craft and reviewing the science data returned by those craft. There are three planned operating modes of the software, each designed for a specific task, although there will be crossover. Each mode will have differing requirements for display and interaction and these requirements have provided a baseline against which to evaluate immersive technologies. One mode will be a "bird's eye view" in which the viewpoint is not tied to the rover. This mode will be useful for route planning for the rover using a terrain model derived from stereo and range data returned from the rover combined with orbital and descent imagery. Another mode will provide an "egocentric" view in which the viewpoint mimics the view from the imaging platform on the rover, and movements of the users head and other inputs may be used to schedule rover observations and sampling activities. A third mode will be used to display rover system status graphically via display of a color coded rover CAD model and the JPL developed Cybergrid. These modes, and some system requirements of each, are summarized in Table 1. The requirements reviewed for each mode include display resolution, stereo display capability, low latency and response time, ability to support multiple users, level of immersion experienced, flexibility in accepting input from various devices, comfort, cost, and scalability. Each mode was evaluated to determine how important each requirement was for that mode.

Table 1: Evaluation of Potential Requirements for Operational Modes

Requirements	Rover Centric	Bird's Eye View	Status Display
Resolution	Medium	High	Medium
Stereo	Low	High	Low
Low Latency	Very High	Medium	Medium
Multi-user	Low	High	Medium
Sense of Immersion	High	Medium	Low
Input Flexibility	Low	High	High
Comfort	High	High	High
Low Cost	Medium	Medium	Medium
Scalability	Low	High	Medium

An immersive visualization system consists of both software and hardware components. Software was evaluated based on requirements for standards-based, real-time rendering performance, cost, and extensibility. Several public domain and commercial packages were evaluated. In general, the commercial packages do not offer the flexibility and extensibility to work with the variety of data types expected to justify their cost. Useful public domain packages include the Visualization Toolkit (VTK) from the

University of Rochester and General Electric and the Minimal Reality (MR) toolkit from the University of Alberta.

Hardware consists of devices to get input from the user, and display data to the user. Different hardware configurations permit different operating modes and feature tradeoffs in interfacing, cost, and performance. Typical quality considerations include latency, resolution, comfort, suitability for the operating paradigm, and stereoscopic vs. monoscopic. A straightforward set of input devices has been considered including Ascension Flock of Birds magnetic tracker, Magellan 3-d mouse, Spaceball, and Dialbox, in addition to the standard mouse and keyboard. The magnetic tracker will be used in conjunction with a head mounted display (HMD) to monitor the users head position (6DOF) and adjust the view accordingly for a true immersive display. Issues involved with the magnetic tracker include working volume, interface, and filtering to reduce a fairly high level of jitter. The other 6DOF input devices (Spaceball and Magellan) and the Dialbox are inexpensive (<\$500) and will be acquired to provide a testbed to gather data about user preferences and interface design.

Display hardware considered includes standard high resolution computer monitors in both stereo (Crystal Eyes or anaglyphic) and mono mode, head mounted displays, the workbench, floccouch, and multi video projection systems. Displays can be generally categorized on a scale from less immersive to more immersive with field of view and head tracking being factors in this consideration. The least immersive system considered is the standard computer monitor. Its features include reasonable cost, high resolution, high comfort, and mono or stereo display. A recent paper [Volbracht] suggests that stereoscopic display can significantly enhance performance of some spatial comprehension tasks, and this combination of factors has led this display paradigm to be favored for the sortie planning phase of rover control. This system is easily scalable to the workbench, a horizontal stereoscopic projection system, which features good ergonomics, high resolution, and high capability for multiple simultaneous users. The ability to support multiple users is considered very important for sortie planning, and the workbench is our prime candidate for this type of activity. In the same family of display are multi-projector systems in a variety of configurations including stereoscopic, monoscopic, edge-blended, and the CAVE where stereoscopic projectors cover four surrounding walls. These systems are essentially the same with the tradeoff being more projectors for more money, and more graphics processing hardware needed to drive them. At the more immersive end of the scale are head mounted displays from a variety of manufacturers. Our test unit is a Liquid MRG-3 monoscopic display with 57,600 pixels over an 84° horizontal field of view. The HMD may be effective for the rover-centric mode of operations because of its ability to provide a true immersive environment when coupled with head tracking. Tradeoffs for HMD selection are stereo vs. mono, resolution, comfort, and field of view, all vs. cost. Higher end systems include high resolution stereo HMDs and the Fakespace BOOM which also includes mechanical position tracking. The Flostation/Flocouch is also being evaluated for its superior ergonomics and high sense of immersion. These technologies are summarized in table 2.

Table 2: Comparison of Immersive Technologies vs. Requirements

Requirements	Monitor	Crystal Eyes	Mono HMD	Stereo HMD	Flocouch	Workbench
Resolution	High	High	Medium	Medium	Medium	High
Stereo	No	Yes	No	Yes	No	Yes
Low Latency	Low	Low	Low	Low	Low	Low
Multi-user	Yes	Yes	No	No	No	Yes
Sense of Immersion	Low	Low-Medium	Medium-High	High	Medium-High	Medium
Input Flexibility	High	High	Low	Low	Medium	High
Comfort	High	High	Medium	Medium	Very High	High
Low Cost	Yes	Yes	Medium	No	No	Medium
Scalability	High	High	Low	Low	Medium	High

Additional technologies of interest include haptic (force feedback), tactile (touch), and true 3D audio. These technologies will be evaluated during the course of the task as cost and time constraints permit. Tactile is of special interest, due to the high potential to enhance terrain understanding through the sense of touch, and potential low cost.

4.0 MODELLING TERRAINS

The Robotic Arm Mission Planning System (RAMPS) task has the goal of developing the underlying modelling technology for supporting missions involving robotic arms and rovers. Three-dimensional models of terrain areas are an invaluable asset in planning operations and in reviewing the predicted and telemetered operations of a robot arm. The RAMPS task has the initial goal of supporting the Mars Volatiles and Climate Surveyor (MVACS) team during the Mars '98 mission. This mission expects to have orbital imagery from Mars Global Surveyor (MGS), descent imagery from the lander, and lander imagery from a stereo imager similar to the Imager for Mars Pathfinder (IMP) used during the Pathfinder mission. These three sources of imagery will be combined to create a multiresolution terrain model with very high resolution detail available within the area of operations of the MVACS arm. The system will be extended to also support rover operations during the Mars '01 and Mars '03 missions.

Figure 3 gives an overall block diagram of the terrain modelling system. Figure 4 gives another computer generated view of the terrain area around the MPF lander. The three primary sources of data for generating terrain models are orbiter imagery, descent imagery, and lander imagery. Each type of imagery is partially processed independently, then combined with data derived from the other sources to create the multiresolution terrain models. Many of the processing steps described in the block diagram and in the following text have been developed as part of a variety of tasks within JPL. A key goal of this task is to identify the portions already developed and establish the necessary steps to integrate those technologies into the overall system.

The orbiter imagery is further classified into two subcategories, lower resolution images and higher resolution images. These two categories are rather arbitrary but are intended to distinguish the types of processing likely to be performed on each type. The lower resolution images are categorized as those which are likely to contain recognizable landmarks, be very nearly a nadir view, and have sufficient overlap with adjacent images that stereo correlation and processing are possible. The higher resolution images will tend to

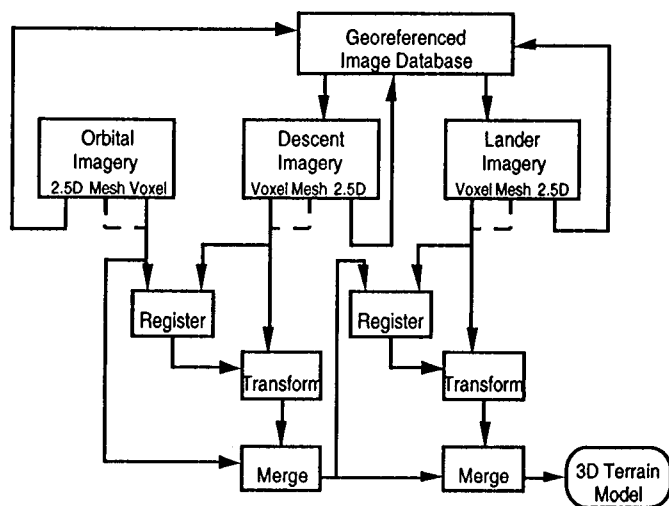


Figure 3: Terrain Modelling System Block Diagram

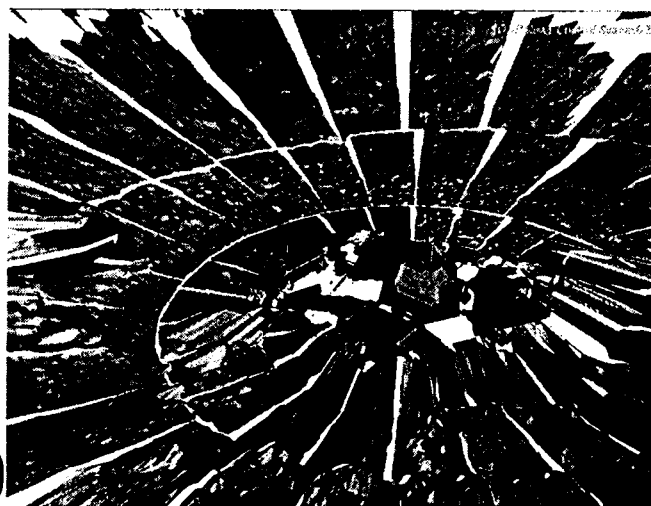


Figure 4: Computer Generated Terrain Image

cover a smaller area of the planet, have little or no overlap with each other, and may be somewhat oblique in view angle. Work on registration of multiresolution orbital imagery has been in progress for several years within the Multimission Image Processing Lab (MIPL) at JPL and many tools have been developed to assist in this process. These tools have been used to support a variety of missions including Viking I and II, Magellan, and Mission to Planet Earth.

Work on analysis of descent imagery is also underway at JPL. The Robotic Vision group is collaborating with Malin Space Science Systems, Inc., in developing tools for constructing 3D terrain models using descent imagery only. These tools use spacecraft descent parameters to estimate the regions of overlap between consecutive pairs of descent images, apply image registration techniques to correct for pointing errors, then extract elevation data from stereo processing of the image pairs. Each consecutive pair yields a smaller

region of higher resolution than the previous pair. Sequentially registering each image to the previous one, beginning with the final one captured and proceeding back to the initial, high altitude image, allows for the identification of the landing site in each image. It is then a simple step to register the initial image to the georeferenced orbital images to georeference the descent images and identify the geocoordinates of the landing site.

Stereo image processing of lander imagery was initially performed by the Robotic Vision group at JPL in support of Mars Pathfinder. The stereo models thus generated were further processed by tools developed under the SOAP task into 3D models suitable for use by the RCW for rover operations. These models were properly referenced to the lander but were not georeferenced as this step was unnecessary for the relatively short range of operations of Sojourner. Future missions will require these models to be georeferenced and integrated with the models generated by orbital and descent imagery.

Two techniques show promise for performing this process and registering the models from the lander imagery to the baseline model. One technique is to reproject the models into an orthonormal view and then use two-dimensional methods to register the images to orbital and descent imagery. A difficulty is the inherent change in resolution across the orthonormalized image and research is needed to resolve this problem. An additional method which is being worked on at JPL is 3D registration of the 3D models. Methods of registering polygonal surface models are being developed by the Robotic Vision group. These techniques use optimization techniques to match the 3D surface of the terrain model generated from the lander imagery to a similar 3D surface generated from the baseline model. The resulting match parameters are then used to correct the position and orientation information for the lander. A similar approach under development in the VESA group uses volumetric primitives (voxels) to represent the terrain to be matched. Voxels may have some advantages over the polygonal surface matching methods in that it is easier to represent unknown volumes, such as regions occluded by rocks and hills, and easy to use, multiresolution data structures are available in which to combine the models once they are matched. However, these methods are under development and have not yet been proven to be effective. These techniques are equally applicable to rover imagery. For Mars '01 and '03, the rovers are also expected to carry IMP-like imagers to capture high-resolution stereo imagery of the terrains under exploration and similar techniques will be applied to work with the imagery.

5.0 ADVANCED TELEMETRY VISUALIZATION

The goal of this task is to develop tools and technologies for advanced telemetry visualization through the use of higher-level graphics linked to telemetry parameters. Of primary interest is the use of detailed CAD models of the craft being monitored with links to telemetry events which will produce a response in the view of the model. These responses can range from nonalarm conditions such as wheel rotations or arm joint angles to alarm type indications with specific reactions such as parts changing color or flashing or exploding models to focus on the sensor giving the anomalous reading. This type of tool can aid greatly in visualizing the area which is suffering from an anomalous reading or in replaying the actions of the craft from a section of telemetry data. This tool will reduce the time, training, and experience necessary to successfully interpret telemetry from a spacecraft. Older tools were very manually intensive when it came to interpreting spacecraft telemetry. More recent tools, such as Cybergrid, are very effective at monitoring large numbers of telemetry items for health as it can identify values within and outside of nominal ranges in an easy to recognize manner. However, it is still up to the operator to try to convert the telemetry reading into a specific problem and to mentally visualize the problem in the context of the spacecraft as a whole. This tool will tie the telemetry to a detailed CAD model which can react to the telemetry in a predetermined way. For example, telemetry from the Sojourner rover can be replayed to illustrate rocker arm movements and wheel rotations. Fault conditions can cause the suspect region to flash a color, perhaps red if overheating or blue if too cold. The model provides immediate feedback on the part of the craft giving the fault which can speed up fault isolation and corrective response.

The ATV system is intended to be a generic system which is configurable for any mission. The project provides an Open Inventor model of the spacecraft and a Telemetry Description File (TDF) specifying the relationship of telemetry channels to model responses. The visualization system loads this information, queries the telemetry data files, and provides visualization of spacecraft behavior. This provides a generic interface to allow adaptation of the system for multiple missions. The UCLA team will use their expertise in the MVACS system design and telemetry specifications to develop the model of the MVACS for integration into this tool. This would then become an operational tool for use during the Mars '98 mission. Of

particular importance will be models of the robotic arm and the sampling devices. These may be very sophisticated and have significant amounts of telemetered data.

The following represents a set of the key features of the ATV tool in the context of the Mars Pathfinder mission and the Sojourner rover:

- display rover attitude based on accelerometer data
- display rover articulation based on chassis sensors (bogeys, differential, and APXS deployment)
- display rover position based on dead reckoning (X, Y, heading), and optional traverse trail
- display highest hazard state using color-coding
- camera controls: translate and rotate, zoom, jump to model
- playback controls: step forward/reverse, animate/interpolate at varying speed
- display graphical plots of telemetry data for review
- selection of telemetry channels for display to allow focus on specific activities

These capabilities are layered on top of a higher-level rendering system capable of using more sophisticated, existing models. Open Inventor was chosen as the models are also compatible with Performer, a high performance rendering system, and VRML for distribution over the Web. Thus this system may be used to provide mission status visualizations to the public.

6.0 WEB INTERFACE FOR TELESCEINCE

The Web Interface for TeleScience (WITS) is a tool being developed by the Telerobotic Applications and Research Group at JPL, with support from SoHaR Inc.. WITS enables scientists to participate collaboratively in planetary lander and rover missions from their home institutions. WITS was originally intended for use in the 2001 rover mission to Mars, but it achieved a high level of maturity early enough that it was used in the 1997 Mars Pathfinder mission. There are several motivations for its development. Future rover and lander missions to Mars (i.e. 1998, 2001, and 2003) will be long duration, on the order of a year, so it will not be feasible for the mission science team to reside at JPL for the duration of the mission. A mission planning and visualization tool was needed to enable the mission science team members to participate fully in the mission while being geographically distributed at their home institutions. WITS provides both the visualization of mission data and the collaborative planning tools needed for this scenario. A collaborative planning tool was needed to enable distributed mission scientists to generate the daily mission plan among themselves and with the rover engineering team. WITS provides this collaborative planning capability for all JPL and Internet-connected users. WITS provides this capability by being written in the Java language and being accessed by a common web browser that runs on all major computing platforms and operating systems. . WITS is available online at <http://robotics.jpl.nasa.gov/tasks/scirover/operator/wits/homepage.html>.

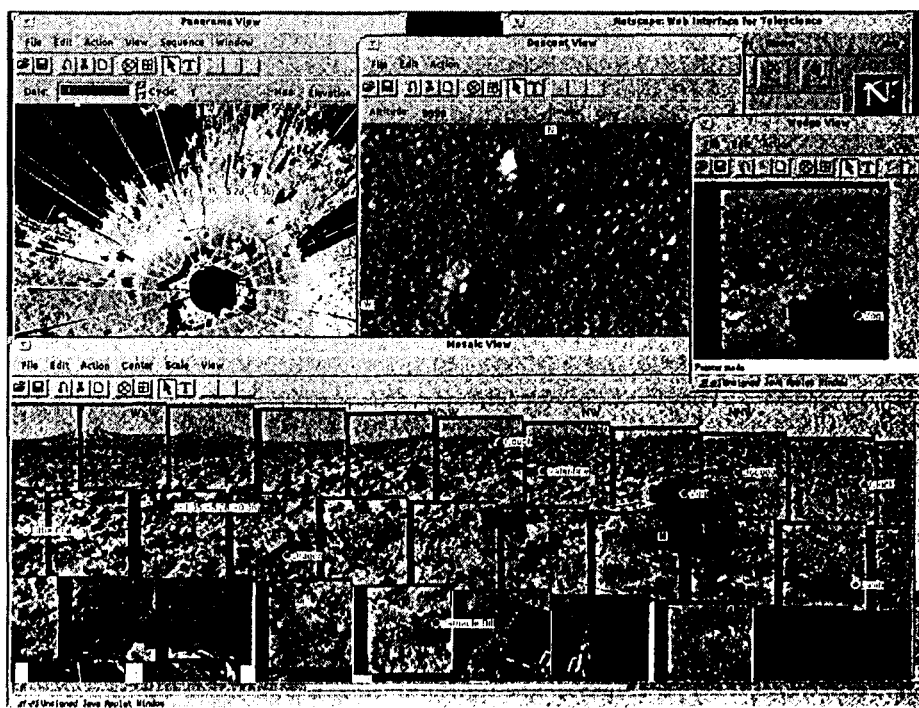


Figure 5: WITS Example Interface Using Sample MPF Data

Different windows of the WITS interface provide various views into the environment surrounding the rover or lander. Examples of these windows are displayed in Figure 5. The Descent View window, upper center in the example, contains down-looking imagery from a descent imager on the lander (the sample data is from Viking as the MPF mission did not include a descent imager). This gives the user a topview of the region of interest and surrounding area. The Panorama View (upper left in the example) provides a topview of the region around the lander or rover as generated from the stereo imagers on the craft. Overlays may be images or color-coded elevation data. The Mosaic View (lower half of the example) provides a view of the entire set of lander images mosaicked into a single panorama. This gives the user a view of the entire surrounding area from the lander's point of view. The Wedge View (upper right in the example) provides a closeup view of a single image from the mosaicked panorama for more detailed examination. An additional view tool, not shown in the example, provides access to the stereo imagery from the rover's cameras and is called the Closeup Tool. An available option is to display anaglyphic stereo in either the Mosaic View or Wedge View to deliver stereo visualization to the user to provide additional understanding of the terrain contours. WITS integrates the various views and provides tools for designating targets, points of interest, waypoints, and other features in each of the tools. Designations in one view are also displayed simultaneously in the other views, providing an integrated suite of tools. Designations are also displayed in the views available for other users across the Web providing collaborative interaction among the science team. WITS provides the tools for giving the science team members a strong understanding of the terrain, along with collaborative tools, to support extensive and elaborate science missions

7.0 CONCLUSION

The Jet Propulsion Lab is moving forward with several efforts to develop enhanced immersive technologies for supporting mission operations. From the highly successful Mars Pathfinder mission through upcoming Mars missions launching in 1998, 2001, and 2003, immersive technologies and systems will aid the operations teams in making mission critical decisions. Creating models of the operational environment and providing visualization tools to explore and interact with that environment are the key aspects being explored. Complete systems which take all the data available and use it to create an immersive environment, enable scientists to interact with the environment and establish science mission goals, collate science requests into mission operations sequences for uplink, rehearse expected activities within the environment, replay actual mission activities based on telemetry, and compare actual operations to predicted operations are on the horizon. Immersive technologies will continue to offer more capability to mission operations teams in the foreseeable future. This will be especially important as exploratory craft gain in autonomy and intelligence and begin to explore farther afield from their initial landing site. Operations will change from precisely specifying number of revolutions of each wheel to broadly defining goals and strategies. Such paradigms require a broader understanding of the environment to facilitate rapid decision making. While the level of immersion can vary from simple two-dimensional displays through stereo displays and virtual workbenches and on up to full immersion with head-mounted displays, haptic and tactile feedback, and intuitive manipulators, the main goal is to provide the operators with a better understanding of the operational environment.

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